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Title: Safeguards for Reactors and Spent Fuel

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# Safeguards for Reactors and Spent Nuclear Fuel

LA-UR-21

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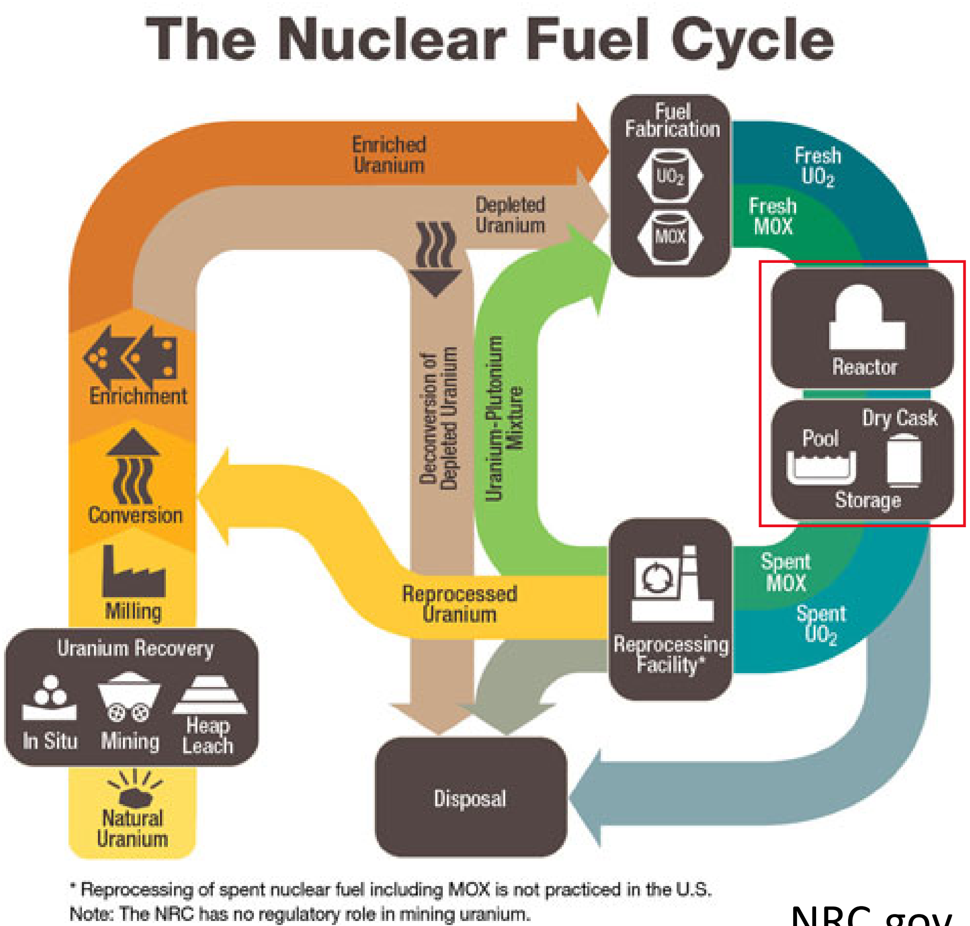
June 30, 2021

# International Nuclear Safeguards




NRC.gov

# Reactors and Spent Fuel

## Why is it relevant to safeguards?

- Highly enriched fuel contains large quantities of $^{235}U$
- Burned fuel may contain large quantities of $^{239}Pu$
  - It is crucial for safeguards that the amount of plutonium going to the reprocessing plant or repository is what we believe it to be
- All nuclear material needs to be accounted for (material accountancy)
  - All nuclear material must be declared to the IAEA
  - There may be a loss of continuity of knowledge in which case fuel needs to be measured to determine how much plutonium and uranium it contains

# Reactor Safeguards

# Safeguards Approach

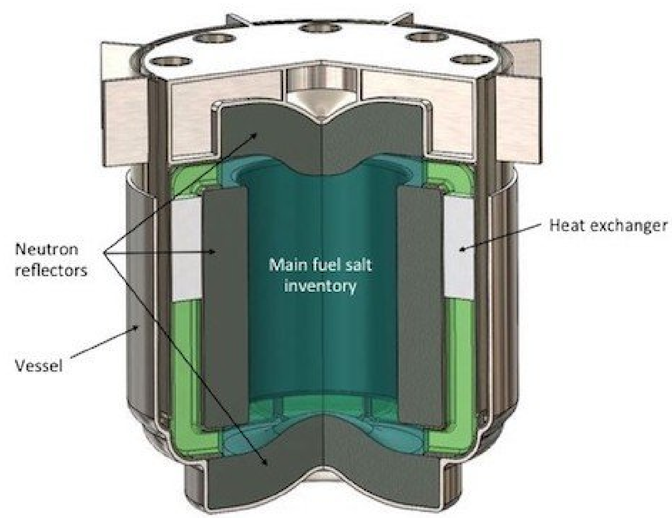
- Gen III Reactors: Accountancy, containment, surveillance
  - Accountancy: Routine interim and physical inventory verification inspections, swipes of areas of interest (destructive analysis), nondestructive assay
  - Containment: Material balance areas
  - Surveillance: Remote monitoring, cameras, sensors
- Advanced Reactors: Work in progress!

# Accountancy

- Item vs Bulk
  - Item form is where integrity of item remains unaltered
    - Reactors, critical assemblies, laboratories, etc.
    - Tags and seals
  - Bulk form is pellets, powders, liquids, gases and accountancy often organized into material balance area (MBA) form
    - Conversion, enrichment, fuel fabrication, reprocessing, etc.
- In item form, items can simply be counted. Uncertainty = 0
- In bulk form, material is in constant movement and may change location, physical form, even chemical composition
- Material quantities are recorded for different balance areas and transfers between balance areas must be recorded as well
  - Receipts and shipments
  - Accidental loss or gain
  - Measured discard
  - Termination of safeguards for non-nuclear use

# Molten Salt Reactors

- Molten Salt Reactors (MSRs) are a relatively new and evolving technology with a strong U.S. presence in development efforts
- The MSR has a closed fuel cycle in which the fuel is a circulating liquid mixture of sodium, zirconium, and uranium fluorides
- The traditional safeguards approach used by the IAEA is not applicable to liquid fuel MSR designs and may be difficult to apply to solid fuel designs.
  - The traditional IAEA approach uses item counting of fresh fuel and spent fuel assemblies before they go into and after they are discharged from the reactor. Additional nondestructive assay methods may be applied if continuity of knowledge is lost on the fuel at any time.
  - For liquid fuel, weight and sampling would likely be required significantly extending time for IAEA verification of facility declaration. For solid fuel, many salts may require cooling and/or cleaning salt off of fuel before verification can occur

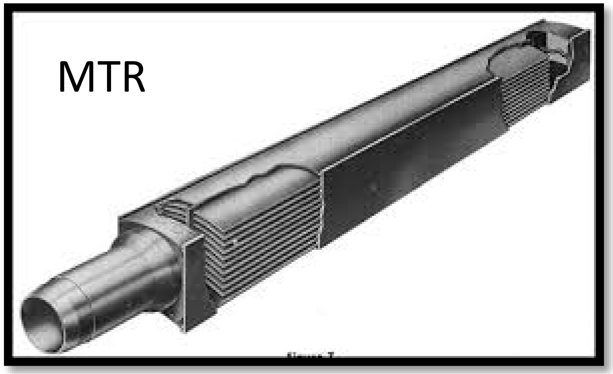


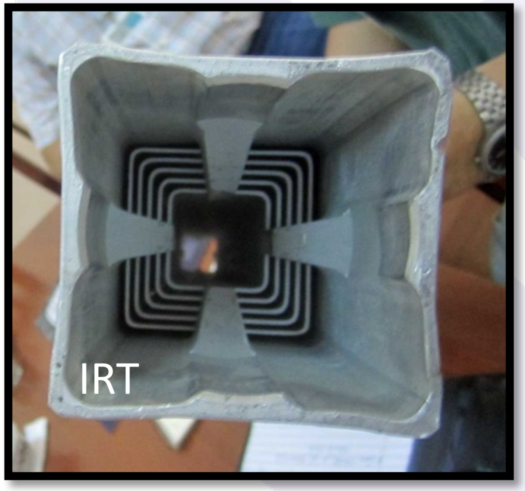

Energy.gov

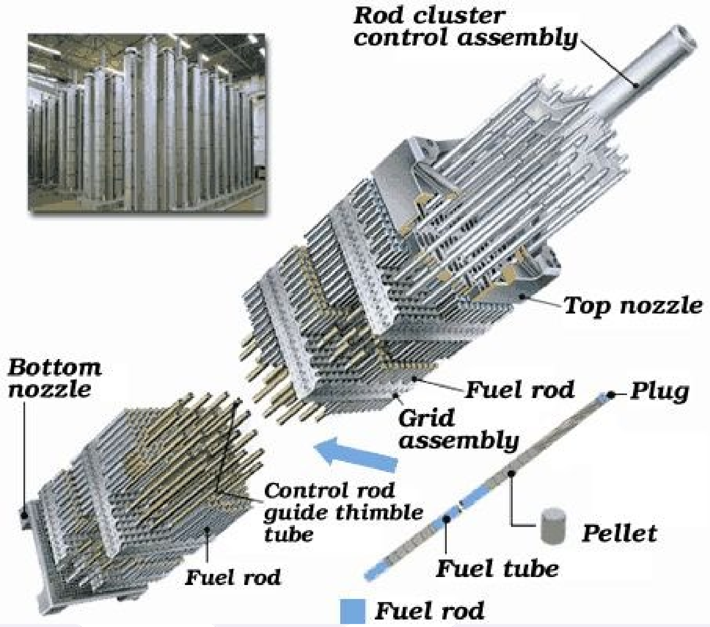
# Spent Fuel NDA

# Spent Fuel NDA: Objectives

- Verify operator declaration of residual uranium, and buildup of plutonium
  - Burnup
  - Initial enrichment
- Verify cooling time of assembly to assist with other parameters
- Verify completeness of assemblies



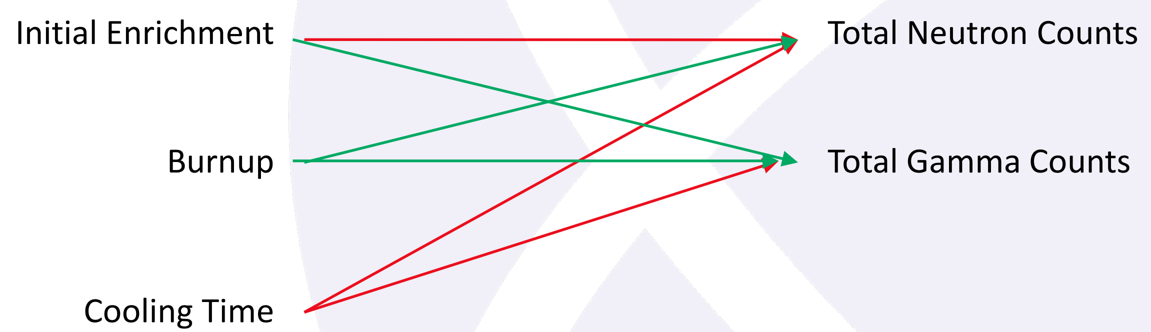




PWR

# Spent Fuel NDA: Challenges

- Interruptions to reactor operations
  - Nuclear facilities have a standard way of operating and large disruptions (i.e. long measurements, drastic fuel movement) are not acceptable
- Fuel inhomogeneity
  - Both axially and radially, neutron flux in the reactor affects burnup, resulting in inhomogeneous fuel assemblies
- Competing parameters




- Very difficult to accurately model
  - Burnup codes are highly dependent on the accuracy of nuclear data and reactor operating history

# Power Reactor vs. Research Reactor

- Why are these two VERY different characterization problems?

| | Power | Research |
|---|---|---|
| **Size** | ~4 m long, 20 cm across, 1000 lbs | ~80 cm long, 8 cm across, 13 lbs |
| **Neutrons** | ~1E8 1/s | ~1E4 1/s |
| **Neutron Emitters** | $^{242}Cm$, $^{244}Cm$, $^{240}Pu$ | $^{240}Pu$ |
| **Operating History** | Predictable, $$$ | Unpredictable, research |
| **Easy Availability of Calibration Standards?** | Nope! | Nope! |

# Currently Employed Techniques

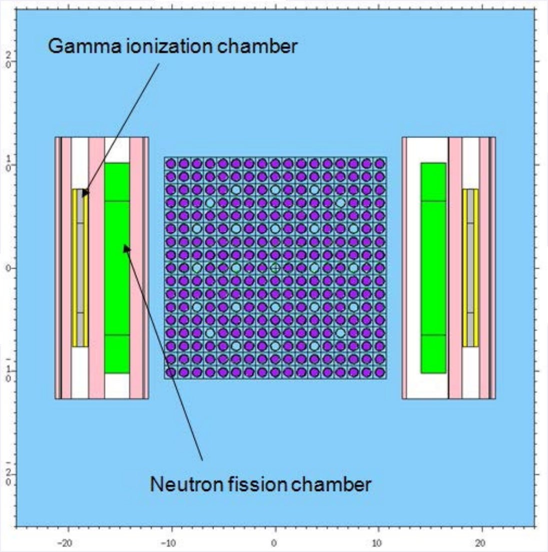
# Fork Detector

- NDA technique widely used by the IAEA and EURATOM
- Detector system straddles light water reactor fuel assemblies with four fission chambers (neutrons) and two ion chambers (gammas)
  - Total gamma and neutron intensities as well as ratios of intensities give information about fuel assembly such as cooling time and burnup
  - One of the fission chambers is wrapped in cadmium to provide a means for estimating multiplication
- Other versions of the Fork detector exist with $^3$He tubes instead of fission chambers, etc

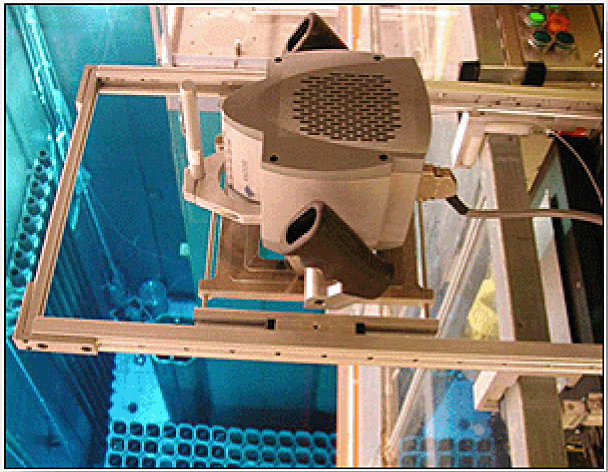
# Fork Detector

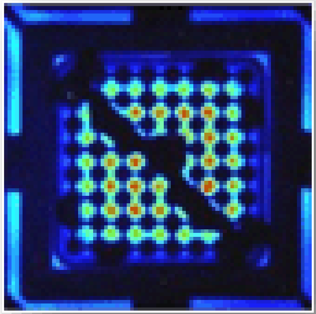
- Benefits
  - Rugged, reliable, validated and verified, easy to use
  - Requires minimal fuel movement

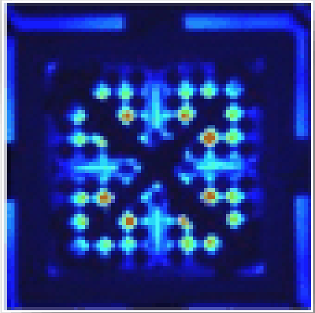
- Drawbacks
  - Asymmetric burnup could affect gamma signal
  - Assumptions about how neutron and gamma counts trend with burnup and cooling time fall apart under irregular burning history
  - Results rely heavily upon data provided by operator
  - May not be able to detect pin removal under 50%



# Digital Cerenkov Viewing Device



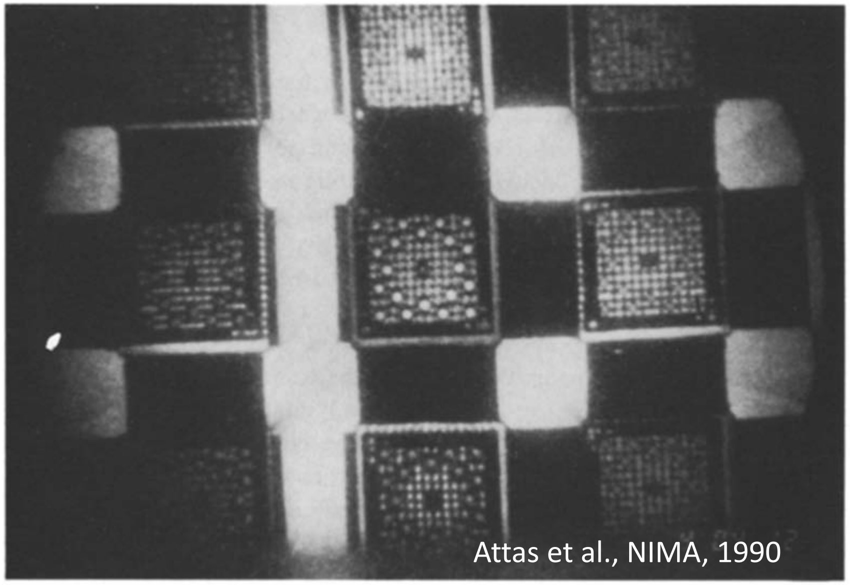




- Viewing device sensitive to ultraviolet radiation in the water surrounding spent fuel
- Cerenkov radiation provides the UV light and is derived from the intense gamma radiation in spent fuel
- Electrons may exceed the speed of light in water and therefore must lose energy by emitting Cerenkov radiation. β particles contribute as well
- Glow patterns above fuel rods used to distinguish fuel from non-fuel

# Digital Cerenkov Viewing Device

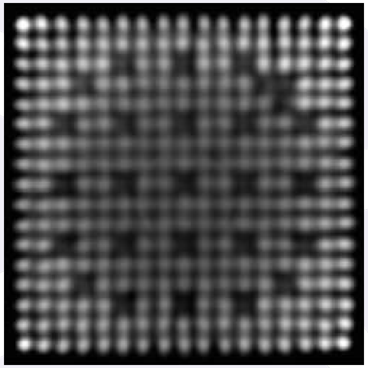
- Benefits:
  - Tested, validated method with reliable history of use
  - Readily detects missing fuel rods
  - Burnup and cooling time verification
  - Indirect measurement method, meaning fuel assemblies may remain in storage positions


Attas et al., NIMA, 1990

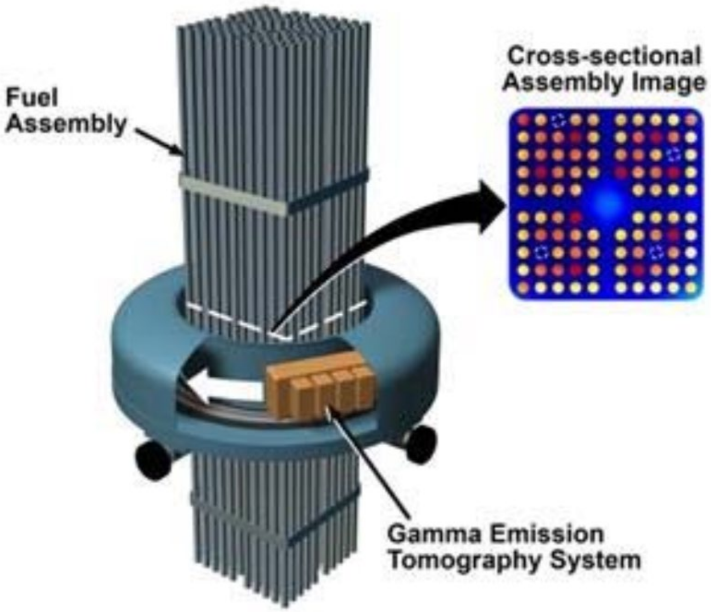
- Drawbacks:
  - Murky water or weak Cerenkov signals can inhibit ability to use CVDs
  - Neighboring assemblies in pool can confuse measurement
  - Limited to certain burnups and cooling times due to required signal strength
  - Potentially easy to fool with cutoff pins or fake fuel rods

# Passive Gamma Emission Tomography (PGET)

- Three simultaneous measurements: gross neutron, gamma spectroscopy, and 2D emission tomography
- Create an axial image of emission locations to detect pin-level diversions
- Measurements take 3-5 minutes



Mayorov et al., IEEE, 2017

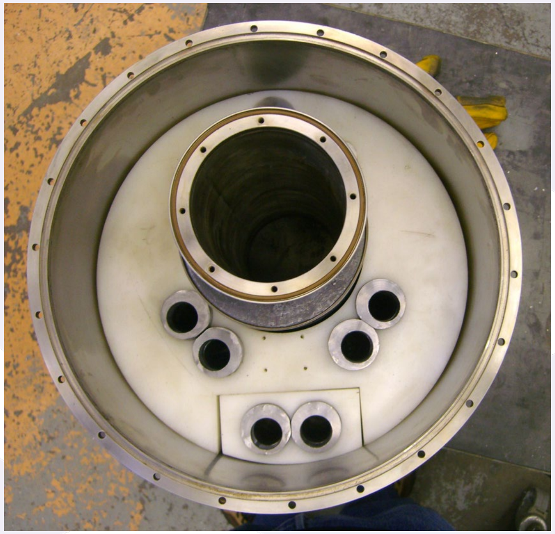



Miller et al., PNNL, 2017

- Neutron data are used for BU, spectroscopy data for CT or to verify non-fuel items
- Has been tested for burnups from 5.7-58 GWd/tU and cooling times from 1.9-27 years

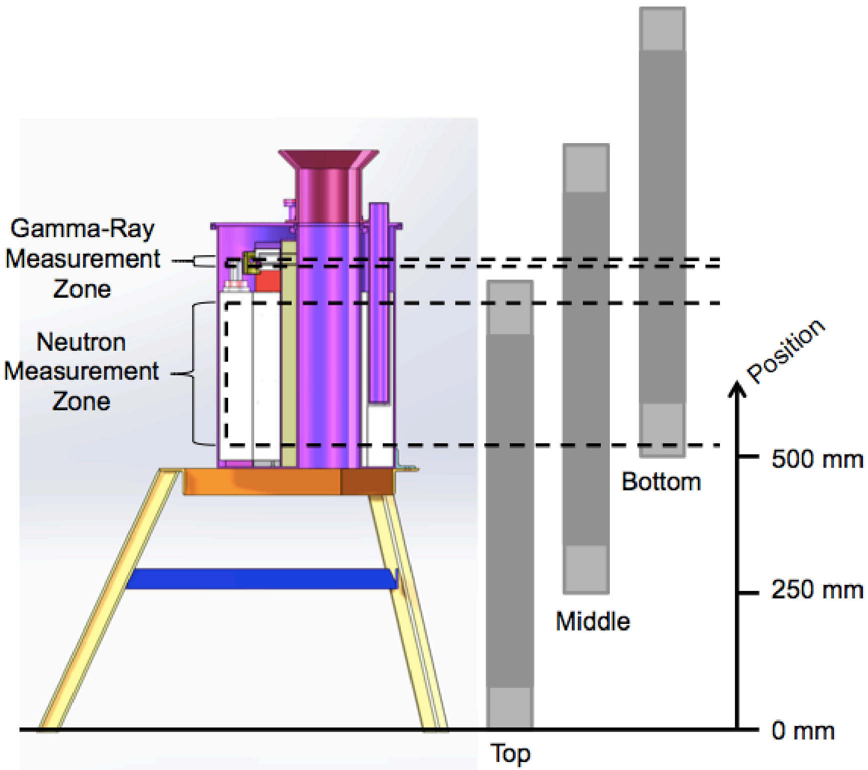
# Advanced Experimental Fuel Counter

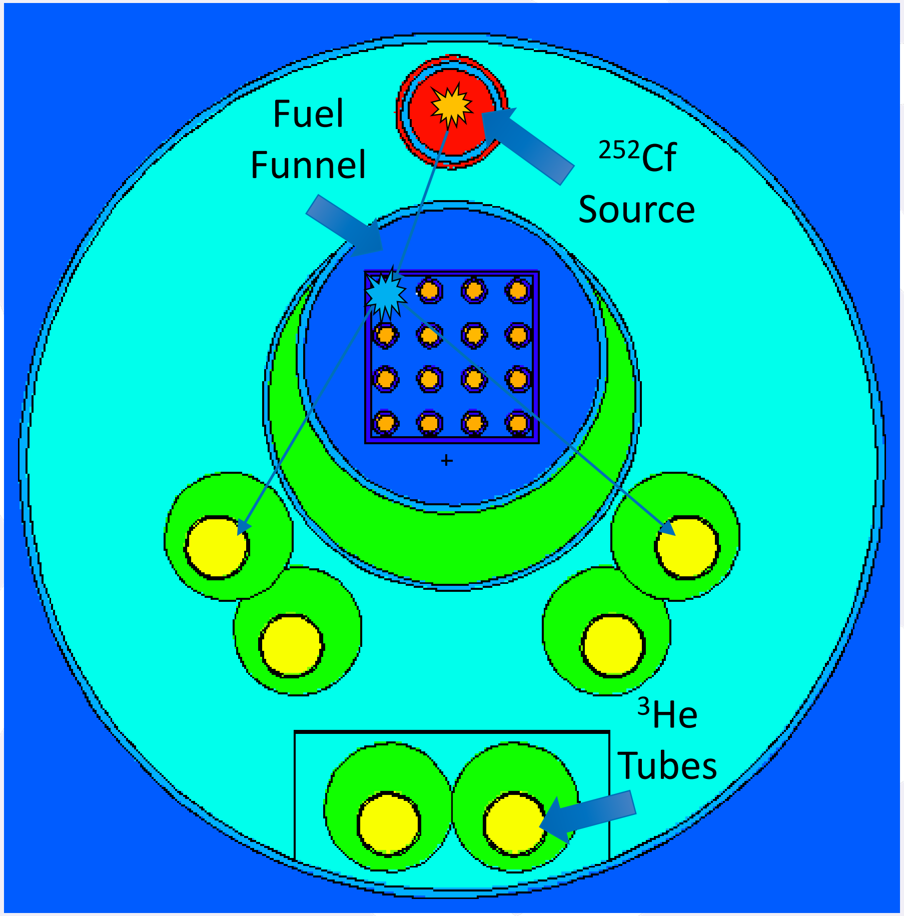
- Designed for research reactor spent fuel characterization
- System uses:
  - Active and passive neutron coincidence counting
  - An ion chamber for gross gamma-ray counting
- Measurement objective is to verify residual fissile mass (i.e., $^{235}U$ + $^{239}Pu$) using active neutron interrogation
- Field trials have occurred as follows:
  - 2006 High Flux Australian Reactor (HIFAR), Australia
  - 2011 Institute of Nuclear Physics (INP), Uzbekistan
  - 2014 Institute of Nuclear Physics (INP), Uzbekistan
  - 2018 Soreq Nuclear Research Center (SNRC), Israel



# Advanced Experimental Fuel Counter

- Measure top, middle, and bottom of assemblies with active and passive interrogation

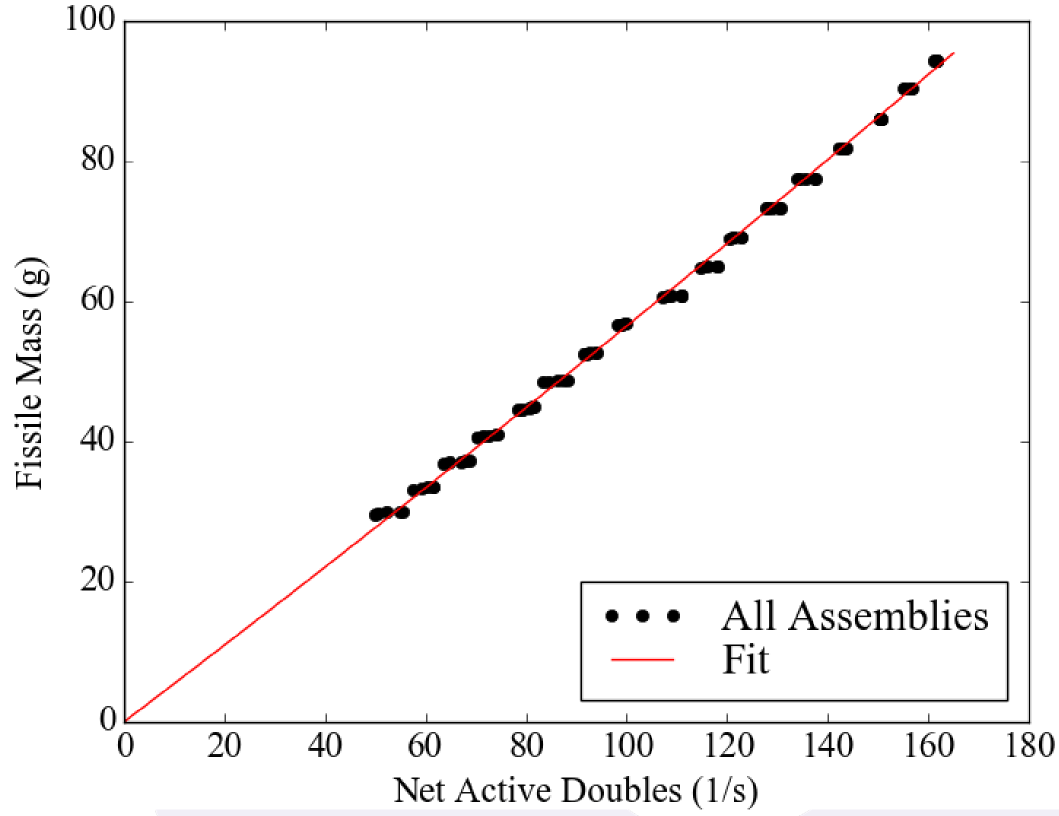


# Advanced Experimental Fuel Counter

Active Doubles – Passive Doubles – Cf Doubles = Net Active Doubles

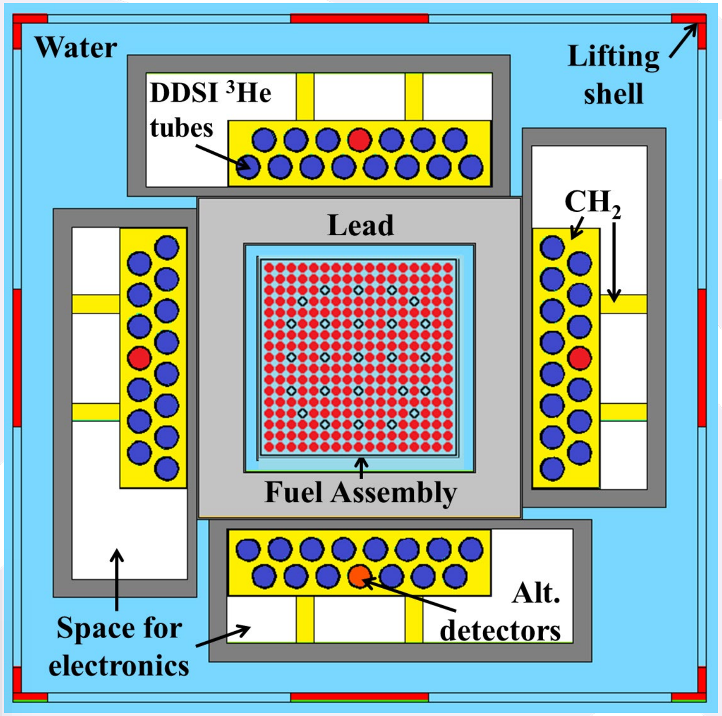
- Net active doubles rate is proportional to residual fissile mass
- But it can vary! Control rod insertion, operating history, assembly rotation, cooling time, can all affect the doubles rate relative to the fissile mass

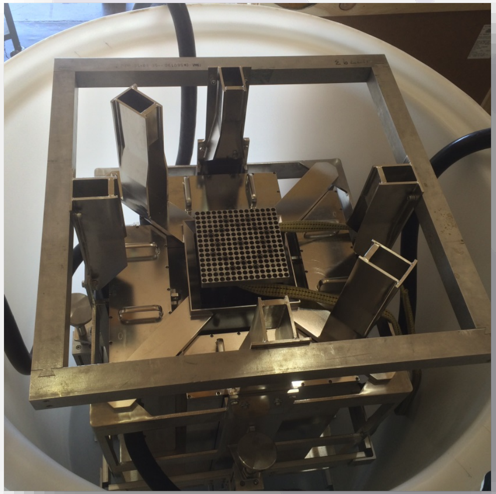


# Experimental Techniques

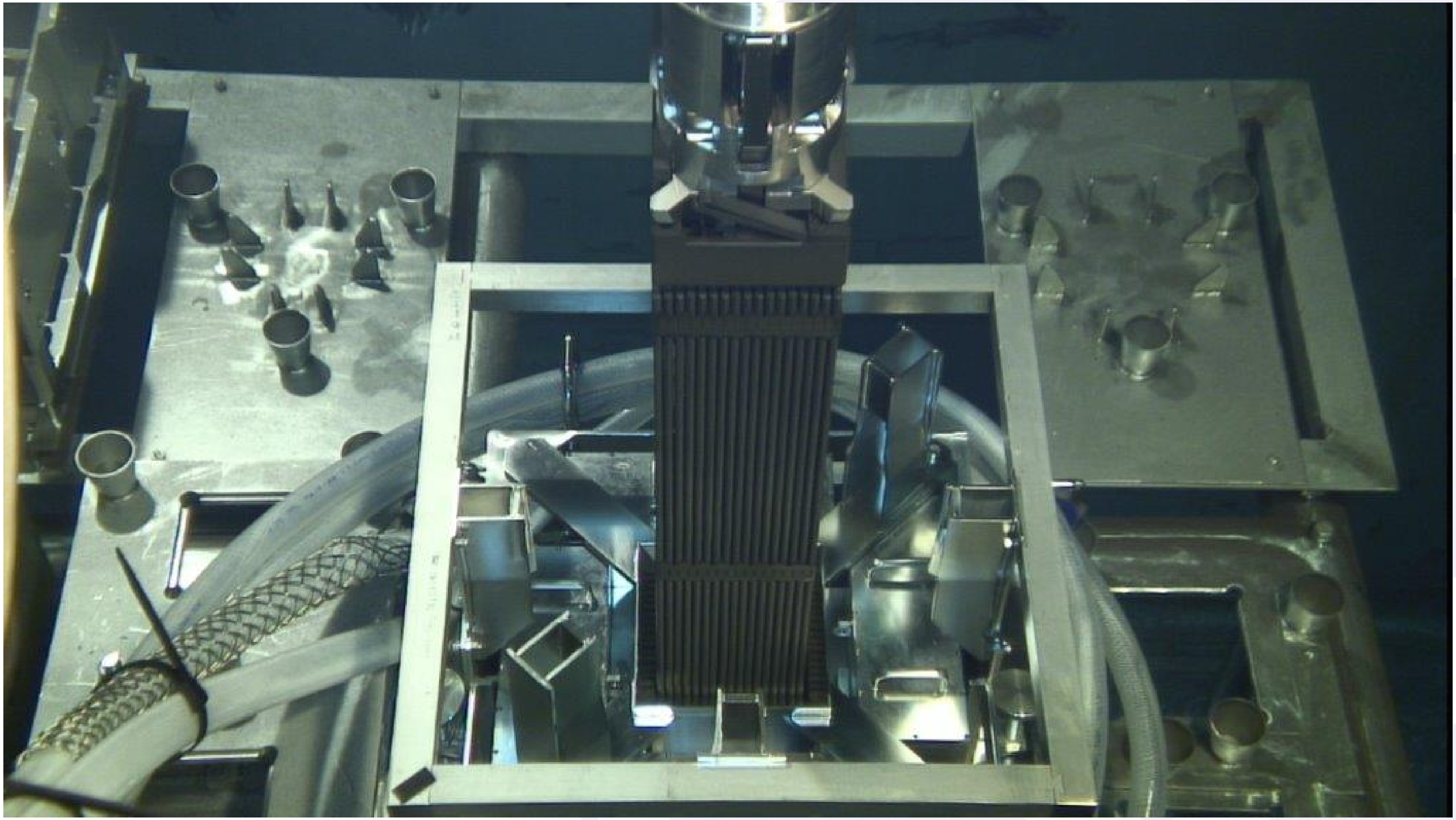
# Differential Die-Away Self-Interrogation

- Spontaneous fission neutrons from $^{244}Cm$, $^{240}Pu$ in spent fuel thermalize in water and interrogate fuel pins
- Neutron coincidence counting: aim to detect two neutrons that are temporally correlated
  - Same fission event, same fission chain
- Record times of neutron detections
  - ➢ *list-mode data*



# Differential Die-Away Self-Interrogation



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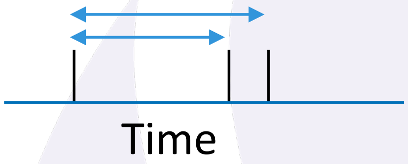
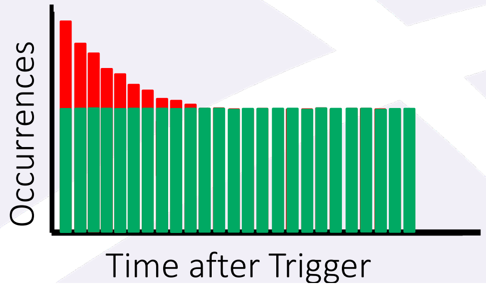
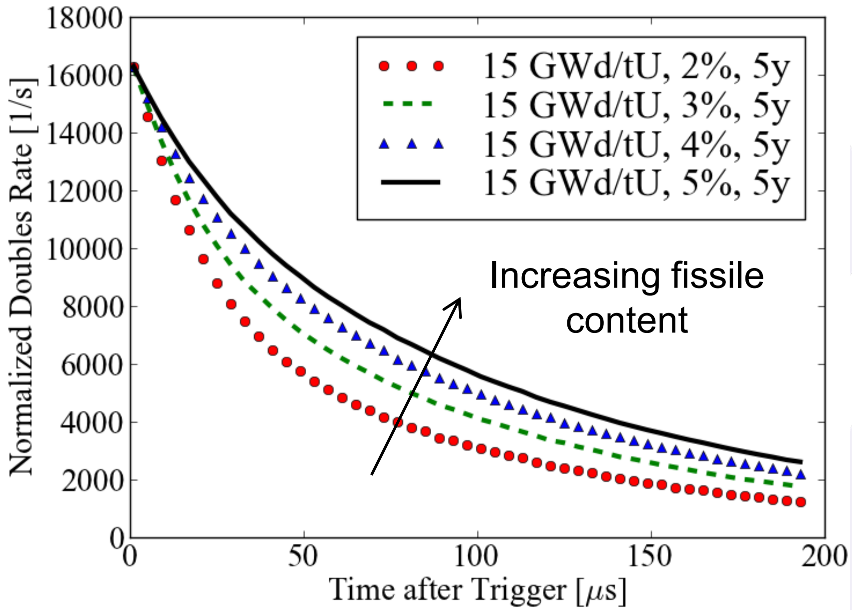
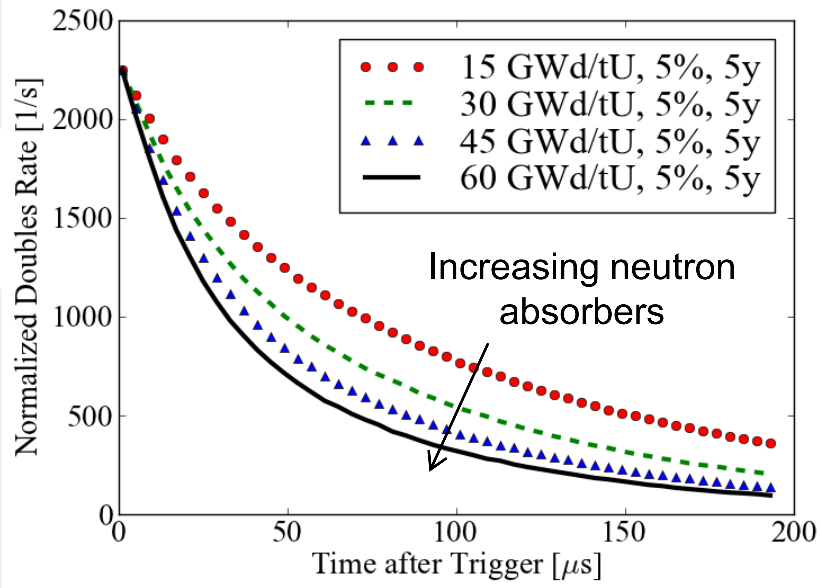
# Differential Die-Away Self-Interrogation

- Rossi-alpha distribution is a histogram of the times between the trigger and each neutron in the gate



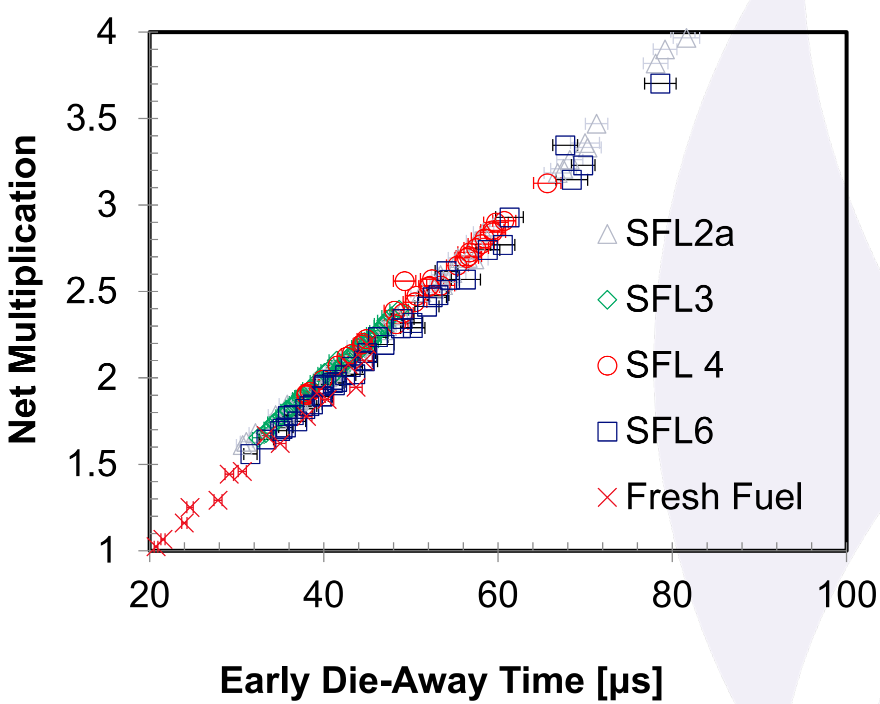



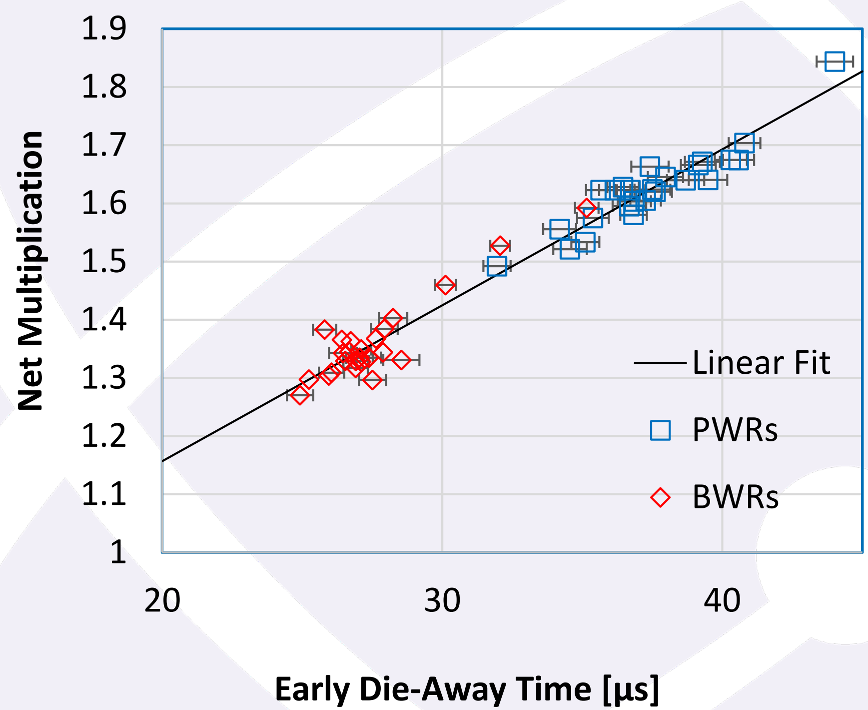



# DDSI Analysis

- Early die-away time is nearly linearly proportional to assembly multiplication
  - Using this indicator, one can determine whether pins have been removed, or confirm BU, IE



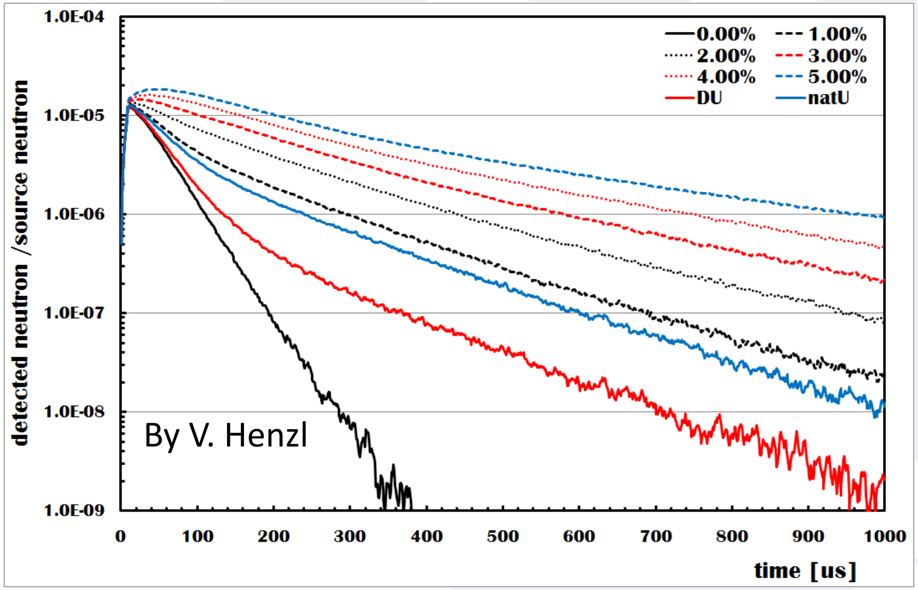

Simulation + Fresh Fuel measurements




Spent Fuel Experiments

# Differential Die-Away

- "Sister Instrument" to DDSI– active version
- External neutron generator provides interrogating neutrons to induce fission
- Record neutron arrival times as a function of time after generator burst
- As fission chains die-away (because the system is subcritical) the induced fission signal dies-away as well

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# Thank you!

Questions?